Experimental Constraints on the Spin and Parity of the $\Lambda_c(2880)^+$

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We report the results of several studies of the $\Lambda_c^+\pi^+\pi^- X$ final state in continuum e^+e^- annihilation data collected by the Belle detector. An analysis of angular distributions in $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays strongly favors a $\Lambda_c(2880)^+$ spin assignment of $\frac{5}{2}$ over $\frac{3}{2}$ or $\frac{1}{2}$. We find evidence for $\Lambda_c(2880)^+ \to \Sigma_c(2520)^{0,++}\pi^{+,-}$ decay and measure the ratio of $\Lambda_c(2880)^+$ partial widths $\frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)} = 0.225 \pm 0.062 \pm 0.025$. This value favors the $\Lambda_c(2880)^+$ spin-parity assignment of $\frac{5}{2}^+$ over $\frac{5}{2}^-$. We also report the first observation of $\Lambda_c(2940)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decay and measure $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ parameters. These studies are based on a $553\,\mathrm{fb}^{-1}$ data sample collected at or near the $\Upsilon(4S)$ resonance, at the KEKB collider.

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Charmed baryon spectroscopy provides an excellent laboratory to study the dynamics of a light diquark in the environment of a heavy quark, allowing the predictions of different theoretical approaches to be tested [1, 2, 3, 4]. There are twelve experimentally observed charmed baryons for which the spins and parities are assigned [5, 6]. They include ground states, spin excitations and lowest orbital excitations. Except for the Λ_c^+, the J^P quantum numbers for these states have not been determined experimentally but are assigned based on the quark model predictions for their masses. There are also six charmed baryons, recently observed at the CLEO [7], Belle [8, 9] and BaBar [10] experiments, for which the spins and parities are not well constrained. The new states are in a mass region where the quark model predicts many levels with small spacing, which makes the J^P assignment difficult. In this Letter we investigate possible spin and parity values of one such state, the $\Lambda_c(2880)^+$ baryon [7, 10], by studying the resonant structure of $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ decays and performing an angular analysis of $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays. We also report the first observation of $\Lambda_c(2940)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decay and measure $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ parameters.

We use a $553\,\mathrm{fb}^{-1}$ data sample collected with the Belle detector at or 60 MeV below the $\Upsilon(4S)$ resonance, at the KEKB asymmetric-energy (3.5 GeV on 8.0 GeV) e^+e^- collider [11]. The Belle detector [12] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer cylindrical drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like array of time-of-flight scintillation counters, and an array of CsI(Tl) crystals located inside a superconducting solenoidal coil that produces a 1.5T magnetic field. An iron flux return located outside the coil is instrumented to detect muons and K_L^0 mesons. We use a GEANT based Monte-Carlo (MC) simulation [13] to model the response of the detector and to determine its acceptance. Signal MC events are generated with experimental run dependence in proportion to the relative luminosities of different running periods.

Λ_c^+ baryons are reconstructed using the $pK^-\pi^+$ decay mode (the inclusion of charge conjugate modes is implied throughout this Letter). To select proton, charged kaon and pion candidates we use the same track quality and particle identification criteria as for observation of the $\Sigma_c(2800)$ isotriplet [8]. The invariant mass of the $pK^-\pi^+$ combinations is required to be within $\pm 8\,\mathrm{MeV}/c^2$ (1.6σ) of the Λ_c^+ mass value, recently measured by BaBar [14]. To improve the accuracy of the Λ_c^+ momentum measurement we perform a mass constrained fit to the $pK^-\pi^+$ vertex. We combine Λ_c^+ candidates with the remaining $\pi^+\pi^-$ candidates in the event. To reduce the combinatorial background we impose a requirement on the scaled momentum of the $\Lambda_c^+\pi^+\pi^-$ combination $x_p \equiv p^*/\sqrt{E^{*2}_{\mathrm{beam}} - M^2} > 0.7$, where p^* is the momentum and M is the invariant mass of the combination, E^*_{beam} is the beam energy, all variables being measured in the center-of-mass frame. To improve the $M(\Lambda_c^+\pi^+\pi^-)$ resolution we perform an interaction point constrained fit to the $\Lambda_c^+\pi^+\pi^-$ vertex.

To measure the $\Lambda_c(2880)^+$ mass and width we apply an additional requirement that either $M(\Lambda_c^+\pi^-)$ or $M(\Lambda_c^+\pi^+)$ be in the $\Sigma_c(2455)$ signal region defined as

$2450\,\mathrm{MeV}/c^2 < M < 2458\,\mathrm{MeV}/c^2$. Whereas 35% of signal events pass this cut, only 12% of background events do so. From MC simulation we find that the mass resolution for the $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays depends strongly on the decay angle θ, defined as the angle between the pion momentum in the $\Lambda_c(2880)^+$ rest frame and the boost direction of the $\Lambda_c(2880)^+$. To assure good resolution for the $\Lambda_c(2880)^+$ mass and width measurement we require $\cos\theta > 0$. This requirement also helps to suppress combinatorial background. The resulting $M(\Lambda_c^+\pi^+\pi^-)$ distribution is shown in Fig. 1. One

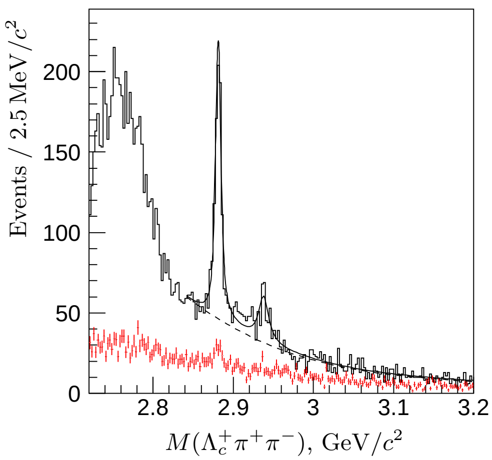

FIG. 1: The invariant mass of the $\Lambda_c^+\pi^+\pi^-$ combinations for the $\Sigma_c(2455)$ signal region (histogram) and scaled sidebands (dots with error bars). The fit result (solid curve) and its combinatorial component (dashed curve) are also presented.

can see clear peaks from the $\Lambda_c(2765)^+$ and $\Lambda_c(2880)^+$. A peak in the region $M = 2940\,\mathrm{MeV}/c^2$ is associated with the $\Lambda_c(2940)^+$ baryon recently observed in the D^0p final state by BaBar [10]. Scaled $\Sigma_c(2455)$ sidebands, which are also shown in Fig. 1, are featureless in the region of the $\Lambda_c(2940)^+$. The $\Sigma_c(2455)$ sidebands are defined as $2438\,\mathrm{MeV}/c^2 < M(\Lambda_c^+\pi) < 2446\,\mathrm{MeV}/c^2$ and $2462\,\mathrm{MeV}/c^2 < M(\Lambda_c^+\pi) < 2470\,\mathrm{MeV}/c^2$.

We perform a binned likelihood fit to the $\Lambda_c^+\pi^+\pi^-$ mass spectrum of Fig. 1 to extract the parameters and yields of the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$. The fitting function is a sum of three components: $\Lambda_c(2880)^+$ signal, $\Lambda_c(2940)^+$ signal and combinatorial background functions. As shown below, the favored spin-parity assignment for the $\Lambda_c(2880)^+$ is $\frac{5}{2}^+$, therefore the $\Lambda_c(2880)^+$ signal is parameterized by an F-wave Breit-Wigner function convolved with the detector resolution function, determined from MC ($\sigma = 2.2\,\mathrm{MeV}/c^2$). The $\Lambda_c(2940)^+$ signal is an S-wave Breit-Wigner function convolved with the detector resolution function ($\sigma = 2.4\,\mathrm{MeV}/c^2$). The background is parameterized by a third-order polynomial. The fit is shown in Fig. 1, and the results are summarized in Table I. The signal yield is defined as the integral of the Breit-Wigner function over a $\pm 2.5\Gamma$ interval.

TABLE I: Signal yield, mass and width for the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$. The first uncertainty is statistical, the second one systematic.

State	Yield	M, MeV/c^2	Γ, MeV
$\Lambda_c(2880)^+$	690 ± 50	$2881.2 \pm 0.2 \pm 0.4$	$5.8 \pm 0.7 \pm 1.1$
$\Lambda_c(2940)^+$	220^{+80}_{-60}	$2938.0 \pm 1.3^{+2.0}_{-4.0}$	$13^{+8}_{-5}{}^{+27}_{-7}$

The normalized χ^2 of the fit is $\chi^2/d.o.f. = 132.2/134$. If the $\Lambda_c(2940)^+$ signal is removed from the fit, the double log likelihood changes by 59.8, which corresponds (for 3 degrees of freedom) to a signal significance of 7.2 standard deviations.

To estimate the systematic uncertainty on the results of the fit we vary the background parameterization, using a fourth-order polynomial and the inverse of a third-order polynomial. We include the $\Lambda_c(2765)^+$ signal region into the fit interval, parameterizing the $\Lambda_c(2765)^+$ signal by an S-wave Breit-Wigner function. The $\Lambda_c(2765)^+$ mass and width determined from the fit are $M = (2761 \pm 1)\,\mathrm{MeV}/c^2$ and $\Gamma = (73 \pm 5)\,\mathrm{MeV}$. We vary the selection requirements; we take into account the uncertainty in the Λ_c^+ mass of $\pm 0.14\,\mathrm{MeV}/c^2$ [14], the mass scale uncertainty of $^{+0.19}_{-0.21}\,\mathrm{MeV}/c^2$ [15] and the uncertainty in the detector resolution of $\pm 10\%$ as estimated by comparison of the inclusive $\Lambda_c^+ \to pK^-\pi^+$ signal in data and MC. In the region between the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ signals the fit is systematically below the data points, which might be due to a presence of an additional resonance or due to interference. We take into account these possibilities as a systematic uncertainty. In each case we consider the largest positive and negative variation in the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ parameters to be the systematic uncertainty from this source; each term is then added in quadrature to give the total systematic uncertainty, quoted in Table I. The main sources of the systematic uncertainty are a possible contribution of the $\Lambda_c(2765)^+$ tail into the fit region (the shape of the tail is not well constrained) and the excess of events between the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ signals. None of the variations in the analysis alters the $\Lambda_c(2940)^+$ signal significance to less than 6.2 standard deviations.

For further analysis, we remove the $\cos\theta > 0$ requirement. To study the resonant structure of the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ decays we fit the $\Lambda_c^+\pi^+\pi^-$ mass spectrum in $M(\Lambda_c^+\pi^\pm)$ bins. By isospin symmetry, we expect equally many decays to proceed via a doubly charged $\Sigma_c(2455)$ ($\Sigma_c(2520)$) as via a neutral one. Since the corresponding doubly charged and neutral channels are kinematically separated in phase space, we combine the $M(\Lambda_c^+\pi^+\pi^-)$ distributions for $M(\Lambda_c^+\pi^-)$ and $M(\Lambda_c^+\pi^+)$ bins. To fit the $\Lambda_c^+\pi^+\pi^-$ mass spectra we use the same fit function as described above. The $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ parameters are fixed to the values in Table I.

The $\Lambda_c(2880)^+$ yield as a function of $M(\Lambda_c^+\pi^\pm)$ is shown in Fig. 2. We find a clear signal for the $\Sigma_c(2455)$ and an excess of events in the region of the $\Sigma_c(2520)$. We perform a χ^2 fit to the $\Lambda_c^+\pi^\pm$ mass spectrum of Fig. 2 to extract the yields of the $\Sigma_c(2455)$ and $\Sigma_c(2520)$. The fitting function is a sum of three components: $\Sigma_c(2455)$ signal, $\Sigma_c(2520)$ signal and a non-resonant contribution. The $\Sigma_c(2455)$ and $\Sigma_c(2520)$ signals are parameterized by a P-wave Breit-Wigner function convolved with the detector resolution functions, determined from MC ($\sigma = 0.9\,\mathrm{MeV}/c^2$ for the $\Sigma_c(2455)$ and $\sigma = 1.5\,\mathrm{MeV}/c^2$ for the $\Sigma_c(2520)$). The mass and width of the $\Sigma_c(2455)$ are floated, while the mass and width of the $\Sigma_c(2520)$ are fixed to the world average values [5]. The shape of the non-resonant contribution is determined from MC assuming a uniform distribution of the signal over phase space. The fit is shown in Fig. 2. We find the ratios of $\Lambda_c(2880)^+$ partial widths $\frac{\Gamma(\Sigma_c(2455)\pi^\pm)}{\Gamma(\Lambda_c^+\pi^+\pi^-)} = 0.404 \pm 0.021 \pm 0.014$, $\frac{\Gamma(\Sigma_c(2520)\pi^\pm)}{\Gamma(\Lambda_c^+\pi^+\pi^-)} = 0.091 \pm 0.025 \pm 0.010$ and $\frac{\Gamma(\Sigma_c(2520)\pi^\pm)}{\Gamma(\Sigma_c(2455)\pi^\pm)} = 0.225 \pm 0.062 \pm 0.025$, where the uncertainties are statistical and systematic, respectively. The $\Sigma_c(2455)$ parameters determined from the fit $M = (2453.7 \pm 0.1)\,\mathrm{MeV}/c^2$ and $\Gamma = (2.0 \pm 0.2)\,\mathrm{MeV}$ are consistent with the world average values [5]. The normalized χ^2 of the fit is $\chi^2/d.o.f. = 106.6/75$. The significance of the $\Sigma_c(2520)$ signal is 3.7 standard deviations.

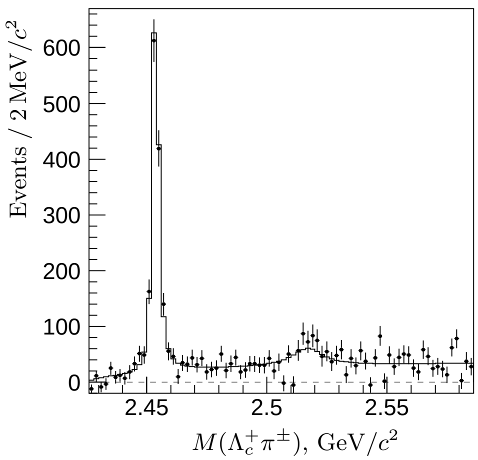

FIG. 2: The $\Lambda_c(2880)^+$ yield as a function of $M(\Lambda_c^+\pi^\pm)$. The histogram represents the result of the fit.

To estimate the systematic uncertainties on the ratios of $\Lambda_c(2880)^+$ partial widths we vary the $\Lambda_c(2880)^+$ parameters, fit interval and background parameterization in the fit to the $M(\Lambda_c^+\pi^+\pi^-)$ spectrum; we vary the $\Sigma_c(2520)$ parameters; we allow the shape of the non-resonant contribution to float in the fit, parameterizing it with a second-order polynomial multiplied by a threshold function or by a third-order polynomial; we take into account the uncertainty in the detector resolution and in the reconstruction efficiency. None of the variations reduces the significance of the $\Sigma_c(2520)$ signal below three standard deviations.

To perform angular analysis of $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays we fit the $\Lambda_c^+\pi^+\pi^-$ spectrum in $\cos\theta$ and ϕ bins for the $\Sigma_c(2455)$ signal region and sidebands. Here, ϕ is the angle between the $e^+e^- \to \Lambda_c(2880)^+X$ reaction plane and the plane defined by the pion momentum and the $\Lambda_c(2880)^+$ boost direction in the rest frame of the $\Lambda_c(2880)^+$. Figure 3 shows the yield of $\Lambda_c(2880)^+$ as a function of $\cos\theta$ and ϕ, after $\Sigma_c(2455)$ sideband subtraction (to account for nonresonant $\Lambda_c^+\pi^+\pi^-$ decays) and efficiency correction.

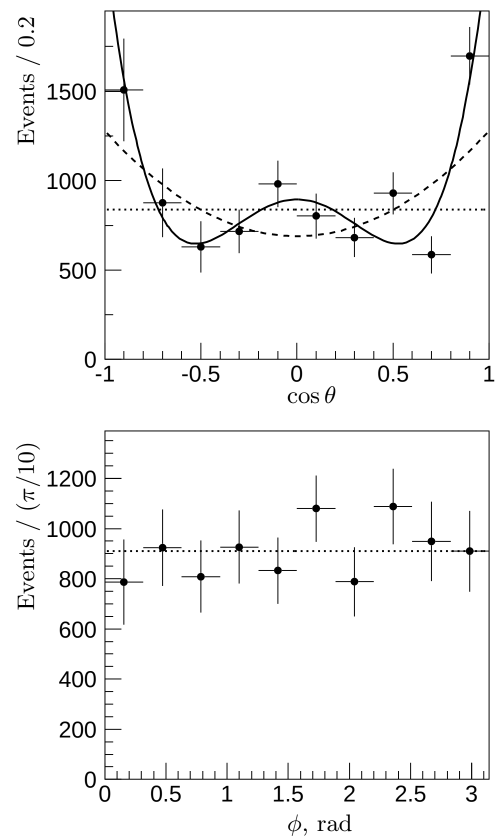

FIG. 3: The yield of $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays as a function of $\cos\theta$ and ϕ. The fits are described in the text.

The parameterization of $\Lambda_c(2880)^+ \to \Sigma_c(2455)\pi$ decay angular distributions depends on the spin of the $\Lambda_c(2880)^+$. For the spin $\frac{1}{2}$ hypothesis both $\cos\theta$ and ϕ distributions are expected to be uniform [16]. χ^2 fits to a constant are shown in Fig. 3 by a dotted line. The agreement is good for ϕ: $\chi^2/d.o.f. = 5.3/9$, but poor for $\cos\theta$: $\chi^2/d.o.f. = 46.7/9$.

The angular distribution for the spin $\frac{3}{2}$ hypothesis

is [16]

$$W_{3/2} = \frac{3}{4\pi}[\rho_{33}\sin^2\theta + \rho_{11}(\frac{1}{3}+\cos^2\theta) - \frac{2}{\sqrt{3}}\mathrm{Re}\rho_{3-1}\sin^2\theta\cos 2\phi - \frac{2}{\sqrt{3}}\mathrm{Re}\rho_{31}\sin 2\theta\cos\phi],$$

where ρ_{ij} are the elements of the production density matrix. The diagonal elements are real and satisfy $2(\rho_{33}+\rho_{11}) = 1$. Since the measured distribution in ϕ is consistent with being uniform (this also holds separately for $\cos\theta > 0$ and $\cos\theta < 0$ samples), the non-diagonal elements are small. The result of the fit to the $\cos\theta$ spectrum for the spin $\frac{3}{2}$ hypothesis is shown in Fig. 3 with a dashed curve. The agreement is poor: $\chi^2/d.o.f. = 35.1/8$.

The angular distribution for the spin $\frac{5}{2}$ hypothesis is [16]

$$W_{5/2} = \frac{3}{8}[\rho_{55}2(5\cos^4\theta - 2\cos^2\theta + 1) + \rho_{33}(-15\cos^4\theta + 14\cos^2\theta + 1) + \rho_{11}5(1-\cos^2\theta)^2],$$

where non-diagonal elements are ignored. The result of the fit to the $\cos\theta$ spectrum for the spin $\frac{5}{2}$ hypothesis is shown in Fig. 3 with a solid curve. The agreement is good: $\chi^2/d.o.f. = 12.1/7$. We find $\rho_{55} = 0.09 \pm 0.02$ and $\rho_{33} = 0.00 \pm 0.03$. Thus the $\Lambda_c(2880)^+$ populates mainly the helicity $\pm\frac{1}{2}$ states, $2\rho_{11} = 1 - 2\rho_{33} - 2\rho_{55} = 0.82 \pm 0.05$.

The χ^2 difference of the spin $\frac{1}{2}$ ($\frac{3}{2}$) and spin $\frac{5}{2}$ fits is distributed as χ^2 with two degrees (one degree) of freedom, therefore the exclusion level of the spin $\frac{1}{2}$ ($\frac{3}{2}$) hypothesis is 5.5 (4.8) standard deviations.

To estimate the systematic uncertainty in the angular analysis of the $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decay we vary the $\Lambda_c(2880)^+$ parameters, fit interval and background parameterization in the fit to the $M(\Lambda_c^+\pi^+\pi^-)$ spectrum. None of the variations alters the exclusion level of the spin $\frac{1}{2}$ ($\frac{3}{2}$) hypothesis to less than 5.5 (4.5) standard deviations.

The Capstick-Isgur quark model predicts the lowest $J^P = \frac{5}{2}^-$ Λ_c^+ state at $2900\,\mathrm{MeV}/c^2$ and the lowest $J^P = \frac{5}{2}^+$ Λ_c^+ state at $2910\,\mathrm{MeV}/c^2$ [1]. The typical accuracy of quark model predictions is $50\,\mathrm{MeV}/c^2$, therefore the agreement with the experimental value for the $\Lambda_c(2880)^+$ mass is quite good. The lowest spin $\frac{5}{2}$ states are well separated from the next $J = \frac{5}{2}$ levels ($3130\,\mathrm{MeV}/c^2$ for negative and $3140\,\mathrm{MeV}/c^2$ for positive parities) and from $J = \frac{7}{2}$ levels ($3125\,\mathrm{MeV}/c^2$ for negative and $3175\,\mathrm{MeV}/c^2$ for positive parities).

Heavy Quark Symmetry predicts $\mathrm{R} \equiv \frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)} = 1.4$ for the $\frac{5}{2}^-$ state and $\mathrm{R} = 0.23 - 0.36$ for the $\frac{5}{2}^+$ state [2, 17]. The measured value $\mathrm{R} = 0.225 \pm 0.062 \pm 0.025$ favors the positive parity assignment for the $\Lambda_c(2880)^+$.

The $\frac{5}{2}^+$ assignment for the $\Lambda_c(2880)^+$ makes it a special state that lies on the leading Λ_c^+ Regge trajectory, whose lower J^P members are the $\frac{1}{2}^+$ Λ_c^+ and $\frac{3}{2}^-$ $\Lambda_c(2625)^+$. The $\frac{5}{2}^+$ assignment for the $\Lambda_c(2880)^+$ based on a string model for baryons was proposed in Ref. [18].

In summary, from angular analysis of $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays we find that a $\Lambda_c(2880)^+$ spin hypothesis of $\frac{5}{2}$ is strongly favored over $\frac{1}{2}$ and $\frac{3}{2}$. We find first evidence for $\Sigma_c(2520)\pi$ intermediate states in the $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ decays and measure $\frac{\Gamma(\Sigma_c(2520)\pi^\pm)}{\Gamma(\Sigma_c(2455)\pi^\pm)} = 0.225 \pm 0.062 \pm 0.025$. This value is in agreement with Heavy Quark Symmetry predictions and favors the $\frac{5}{2}^+$ over the $\frac{5}{2}^-$ hypothesis for the spin-parity of the $\Lambda_c(2880)^+$. We also report the first observation of $\Lambda_c(2940)^+ \to \Sigma_c(2455)\pi$ decays, and measure the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ parameters.

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